NASA-CR-200802

ANNUAL REPORT AND STATEMENT OF WORK
PEACE Investigation for the Cluster Mission: a Renewal of NASA grant NAG5-2215

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ANNUAL REPORT
Covering 3/1/95 through 2/29/96

Task 1: Cluster/PEACE Operations and Data Processing Planning

Operations Planning

The principal task which we have performed in the past year is planning for Cluster operations (and the PEACE modes which support these operations) and data analysis. The Cluster mission is telemetry-limited: i.e. in one orbit (approximately 47 hours), the spacecraft can acquire, store, and telemeter to Earth either 6 hours of high-resolution mode ("burst mode") data or 24 hours of low-resolution ("normal mode") data, or a combination of the two, with one hour of burst mode being equivalent in telemetry to 6 hours of normal mode. (This is somewhat of an oversimplification; in fact, the spacecraft can operate continuously in normal mode, and an orbit with maximum burst mode data (6 hours) means no data taking at all the next full orbit). The PEACE electron instrument, along with its sister CIS ion instrument, is a 3-D plasma detector. In normal mode, only pitch angle information and a very limited amount of 3-D data may be telemetered to Earth, whereas much of the 3-D data can be acquired in burst mode. Thus our team's project has been to identify those regions of space where burst mode data acquisition is critical to understanding the physics of the processes, and where the 4-spacecraft suite crosses gradients in plasma parameters quickly and the high time resolution of the burst mode is crucial to determining the spatial versus temporal variations observed with the four spacecraft.

Naturally, the regions targeted for burst mode operations include boundaries such as the magnetopause, bow shock, and cusp; but other regions are also important for burst mode such as the solar wind (to determine turbulence characteristics and the 3-D distribution of upsteam electrons) and the auroral zone (to determine spatial versus temporal changes in the auroral electric fields). In addition, the PEACE instrument has several possible modes for burst mode operation: some have finer angular resolution but coarser energy resolution; some have coarser angular resolution but finer energy resolution; and some concentrate on resolving the loss cone at high altitudes (a difficult task because of the low field value).

In the course of several PEACE team meetings this year, the science operations plan has been discussed and tradeoffs made with the other teams (many of whom would prefer normal mode operations to maximize temporal coverage). In addition, standard PEACE modes for each of the regions of space (cusp, magnetopause, solar wind, etc.) have been identified. A few areas of continued negotiation still exist, and these will be resolved in the next few months before launch. The Rice University area of responsibility has been the magnetospheric cusp, magnetopause current structures, and auroral zone.

Data Processing Planning

In this year we also began establishing Rice University as a Remote Data Processing Facility. As part of their Cluster work, David Winningham of the Southwest Research Institute in San Antonio is developing a software product ("SDDAS") which will process level-0 PEACE instrument data and yield numerous kinds of graphical and data product outputs. These products include the generation of color spectrograms, line plots and contour plots of particle distribution functions, flows, and currents. In addition, processed data sets, including inter-spacecraft comparison data sets, can be generated from the level 0 data for further numerical analysis using IDL or other software packages. In addition, analysis software is being developed based on CDF format data by NASA/GSFC and by Queen Mary University.

We are establishing Rice University as a mirror data processing facility. In last year's request we were granted the funds to purchase a Sun workstation essentially identical to that used for the software development at SWRI, and to install and maintain the SDDAS software at Rice University, downloading updates from SWRI as necessary. In this way, the Rice effort would not overload the SWRI system for our own data analysis efforts, and other outside users may log into our system to access the data as well as to SWRI. At present we do not anticipate having the entire data set in an on-line basis (this will be done at SWRI), but we will maintain a substantial portion of the data set online, available for ourselves and other offcampus scientists to use.

We have been following the cost/performance ratings of various workstations presently available, and it has been clear that deferring the purchase of the workstation as long as possible will assure us the most capable facility for the most reasonable price. Thus we have not yet purchased the computer, but plan to do so in the next month. No addtional resources for that facility are requested in this grant, except for 1 month of programmer assistance to get the SDDAS data analysis system online and operating.

This task is under the supervision of Professor Patricia Reiff (P.I.), whose academic year time for this effort is being donated to the project by Rice University.

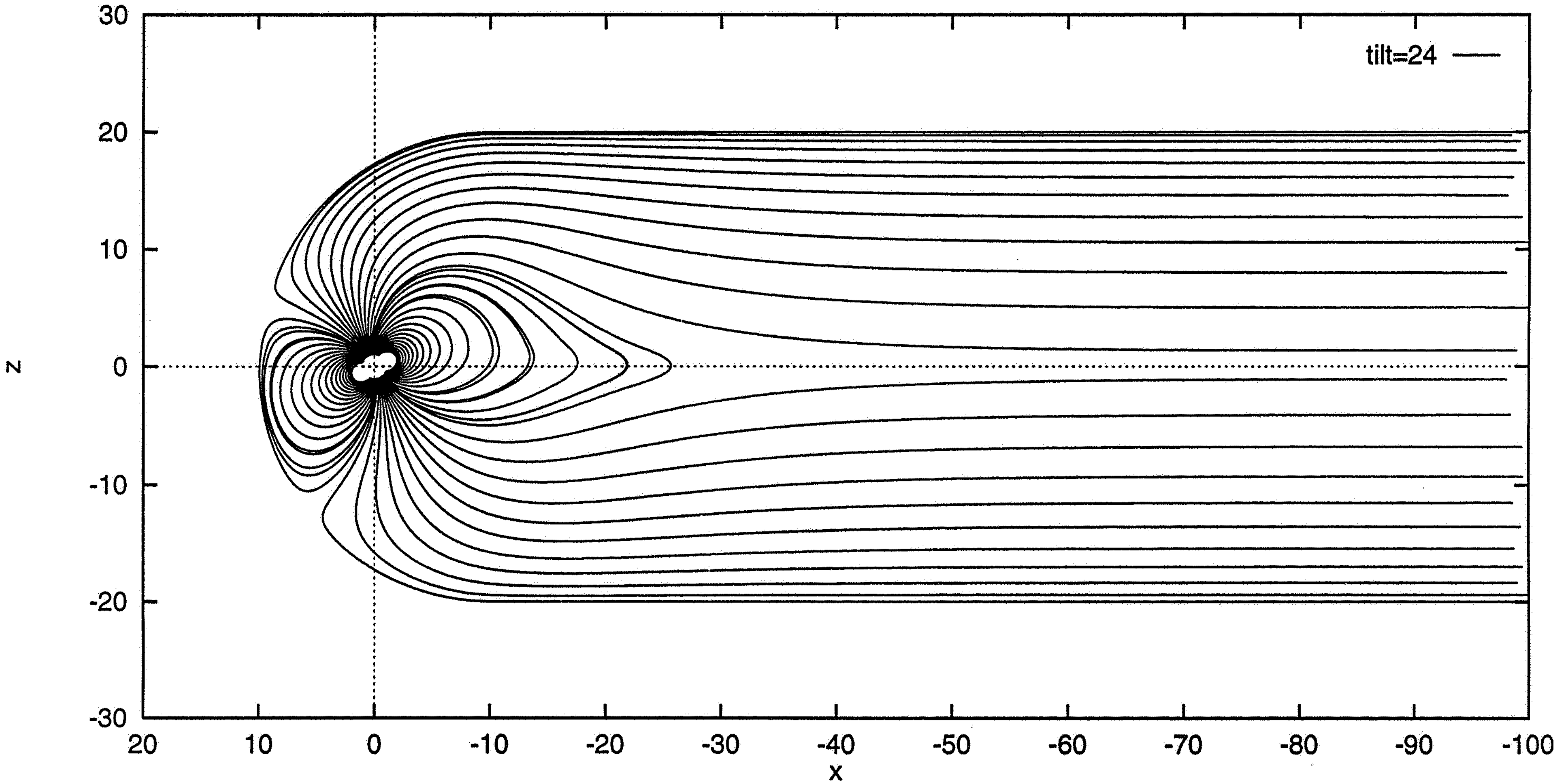
Task 2: Magnetic Field Modeling

The successful conduct of the Cluster mission requires the use of quantitative global magnetosphere models, both for planning of mission operations and for comprehensive data analysis. Existing global models are of three types: (1) global mhd simulations (e.g., NRL/Dartmouth, GSFC/Maryland, UCLA); (2) empirical data-based models (Tsyganenko and colleagues); and (3) modular physical models (Rice). Each type has its own strengths and weaknesses; we propose that the modular physical models are best suited for the mission planning and data analysis tasks at hand. Global mhd simulations are too computer intensive to provide a routine, flexible planning and analysis tool, and they have little control over non-mhd effects that determine the structure and dynamics of sharp boundaries (e.g., magnetopause, cusp) that are the focus of the Cluster mission.. Empirical models fail to resolve sharp boundaries because the models necessarily average over large data sets in which the boundaries are non-stationary, and these models have the additional problem of being parameterized by statistical indices such as Kp rather than by physical variables, such as solar-wind dynamic pressure and IMF vector, that can be monitored in real time.

We have made considerable progress in adapting our open magnetosphere model to the task of Cluster mission planning and data analysis. Three essential tasks have been completed:

(1) We have improved our shielding algorithm to eliminate inaccuracies that appeared for large values of the dipole tilt angle. The enclosed figure illustrates the precise shielding of interior fields (dipole, ring-current, and tail fields) that is now attainable for the most extreme dipole tilt angle. (The full model is, of course, magnetically open, but the model's strength as an analysis tool lies in the fact that the magnetopause normal component distribution is specifiable on physical grounds, and is free of stray normal components arising from imperfect shielding of internal field sources.)

(2) We have optimized the specification of model parameters (e.g., standoff distance, tail radius, tail field strength, ring-current strength) as functions of upstream solar wind and IMF conditions.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(3) The computer code has been debugged and made ready for public use. The Fortran source code is now available at the anonymous ftp site "spacsun.rice.edu" under the directory "/pub/ding/CLUSTER/".

We now have a robust, efficient code that can specify, for given solar-wind/IMF conditions and dipole tilt, the magnetic field configuration of the open magnetosphere and the electric potential distribution as mapped from the solar wind to the polar cap. The needed refinements described above have slowed the code by a factor of two or so, but it is still a versatile research tool. With a modern workstation, the code will trace a single field line in a few seconds and map the entire polar cap magnetic- and electric-field distribution in a few minutes.

Technical aspects and results of this modeling approach have been described in the literature [Toffoletto and Hill, 1989; 1993; Toffoletto et al., 1994; Ding et al., 1994a, 1994b]. Recent improvements, partially supported by this grant, include a ring current and improved tail current, are described in Cheng Ding's Ph.D. thesis [Ding, 1995]. Work has also been completed on the development of a more general Laplace solver that allows an arbitrary magnetopause shape and, more importantly, an arbitrary variation of the magnetopause magnetic normal component distribution, which is essential for introducing the effects of a time-varying solar-wind input [Ding et al., 1995a, 1995b]. The model has been tested by severe events such as the storm of March 24, 1991 [Ding and Hill, 1996] and the magnetic cloud event of October 18-20, 1995 [shown at the "Solar-Terrestrial Theatre" at the fall AGU and posted to the web: http://space.rice.edu/ISTP/cloud.html; will be given at spring '96 AGU]. In addition, we now use the model to routinely post to the World Wide Web a "now" snapshot of the magnetospheric field lines and convection pattern, based on the most recent, near-real-time WIND data (see http://space.rice.edu/ISTP/dials.html). After a decade of effort, we now have in hand a powerful, quantitative modeling tool that is readily adaptable to the operational planning and data analysis requirements of the Cluster mission. We propose here the incremental work that is needed to make this adaptation.

STATEMENT OF WORK

Task 1: Cluster/PEACE Operations and Data Processing

Operations Planning

In the coming few months we will continue to work with the PEACE instrument team and the entire CLUSTER science working team to optimize the burst mode acquisition times and PEACE modes associated with each. Since the schedule is finalized several months in advance, the early part of the mission is being finalized now.

Data Processing Planning

In the next month, we will bring over the SDDAS analysis software to run at first on another departmental Sun. In this way we will train ourselves on the analysis software before committing to the final purchase of the Sun workstation dedicated to Cluster. Similarly, we will bring down the Queen Mary and GSFC analysis routines and become familiar with their operation. We recognize that modules specifically for our studies will need to be programmed to work with these systems, and the programming will begin in earnest. We are eagerly anticipating the launch of Cluster in May and hope to have all basic analysis routines up and debugged well in advance of launch. We realize, though, that many of the special-purpose routines cannot be finished until realistic sample data is obtained.

Task 2: Magnetic Field Modeling

There are three remaining tasks in the area of magnetic field modeling that we propose to accomplish before launch:

(1) Development of an efficient computer code to calculate the open-closed boundary as a function of local time, and predict the time of open-closed boundary crossings on a given Cluster orbit.

(2) Development of a user-friendly interface with the model. Given the ephemerides for a given Cluster orbit, and solar-wind/IMF parameters when available, the interface program would initialize the model parameters and provide the full electric- and magnetic-field configuration, calculate the satellite ground track by mapping the satellite position along model field lines, and predict the times of magnetopause and cusp crossings. This facility would be made available through anonymous ftp and perhaps also through the World Wide Web. Our intention is to create a web page of the cluster orbit with the predicted magnetic field vectors along the orbit, and post that daily to the web, changing the magnetic field vectors in response to IMF data from WIND. The T-H model is presently being posted to the Web in the file http://space.rice.edu/ISTP/dials.html ; the model is presently being refined to be more understandable to the user.

(3) Replacement of the dipole representation of the geomagnetic field by the IGRF to improve the accuracy of mapping between the satellite and correlative ground-based observations.

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Towards a New-Generation Model of the Open Magnetosphere

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IUGG XXI GENERAL ASSEMBLY
IAGA Symposium 314 Magnetospheric Models
Thurdays, July 13, 1995

INTRODUCTION

The Toffoletto-Hill open magnetosphere model [Toffoletto and Hill, 1989; 1993] uses a modular approach to model the magnetic field and a mapping approach to model the electric potential on open field lines.

Magnetic field:

It begins with a closed magnetosphere model [Voigt, 1981], which has a dipole field shielded inside a magnetopause represented by a hemisphere attached to a cylinder. The TH model perturbs this with two magnetic modules, an interconnection field, which models the coupling between the IMF and the geomagnetic field under a given magnetopause normal component distribution, and an additional tail field, which approximates the effect of the tail current.

Electric field:

In the open magnetosphere, the solar-wind motional electric field ($\mathbf{E}=-\mathbf{v}\times\mathbf{B}$) is mapped along open field lines assuming equipotential field lines to drive the convection of plasma in the high latitude ionosphere and magnetosphere. This mapping provides the electric potential on open field lines but not on closed field lines. This limits the application of the model in practice. For example, one such application is to use the mutually consistent electric and magnetic fields to trace particles in the magnetosphere. However, the tracing cannot extend to the closed field line region because the electric field, the gradient of electric potential, is not provided there.

This paper describes recent efforts to improve this existing open magnetosphere model. Among those efforts, the extension of the electric potential to the low-latitude ionosphere was requested by participants at last year's GEM workshop.

I. *MAGNETOPAUSE CURRENT FIELD*

The magnetopause current shields the interior field within the magnetopause and allows only partial penetration of the IMF. The Toffoletto-Hill model describes the partial IMF penetration for a given IMF direction and merging geometry, but is restricted to steady-state conditions in which the IMF direction is independent of distance along the Earth-Sun line. This is due to the difficulty of modeling the magnetopause field.

To model the interconnection field for an arbitrary normal component distribution on the magnetopause, and to be able to shield any kind of interior field, we have developed a more general representation of the magnetic field produced by the magnetopause current. The details of the method are presented in Ding [1995]. Here we show the shielding of a dipole field in Figure 1, which is identical to that of Voigt [1981]. The shielding of a ring current field is described in the next section. The shielding of other types of interior field is presented in Ding [1995].

II. *RING CURRENT FIELD*

The Toffoletto-Hill model, like the Voigt [1981] model on which it based, has no geomagnetic ring current. The lack of a ring current degrades the field representation in the inner magnetosphere and the magnetic mapping in this region [Ding et al., 1994].

To overcome this disadvantage, we adopt the unshielded axi-symmetric ring current model developed by Hilmer and Voigt [1994]. This model, containing both eastward and westward currents, is physically reasonable and operationally flexible [Figure 2a]. Before adding the ring current field to the Toffoletto-Hill model, it has to be rigorously shielded within the given magnetopause surface so that the crucial boundary condition on the magnetopause normal component will not be comprised. This is done by applying the shielding algorithm of Ding [1995] to obtain the result shown in Figure 2b.

III. *ADDITIONAL TAIL FIELD*

The additional tail field lines in the Toffoletto-Hill model are straight lines in the ±x direction in the cylindrical region and semicircles in the hemispheric region [Figure 3a], which removes dayside magnetic flux and transports it to the tail lobe, and consequently makes the polar-cap size, shape and position realistic.

This field implicitly produces an extraneous negative B_z region at the dawn and dusk flanks in the equatorial plane when the IMF has a large southward component, as reported in Ding et al. [1995]. To fix the problem, we first let the nightside tail field lines go straight and pass through the dayside magnetopause, which contributes no southward B_z on the equatorial plane, and then apply the shielding algorithm to satisfy the requirement on the dayside magnetopause. Figure 3b illustrates the new (shielded) additional tail field. The equatorial B_z is now varies three-dimensionally with a maximum southward B_z near the subsolar point, where the surplus southward B_z can be compensated by the shielded ring current field.

This modification also eliminates the spurious current within the dayside magnetosphere, which was produced by the curvature of the field lines. The tail current now extended into the dayside region, is reduced by the ring current there, while in the nightside region it is strengthened by the ring current.

IV. *NEW CONFIGURATION*

We now superpose the shielded dipole and ring current fields and the new additional tail field onto the Toffoletto-Hill model's interconnection field to assemble the new total field configuration. This section compares the results from the new model and the original Toffoletto-Hill 1993 model.

Figure 4 shows the comparison of the field configurations in the noon-midnight meridian between the original TH93 model and the improved version. The IMF is southward with a magnitude of 6 nT. The differences are bigger at the dawn and dusk flanks [Figure 5] than in the noon-midnight plane, owing to the elimination of the extraneous negative B_Z region. We also calculate the polar potential for the same conditions [Figure 6]. The bigger open-field-line region in the new model is the result of the modification of the additional tail field and the inclusion of the ring current.

Since the new magnetopause field model has the ability to handle an arbitrary normal component distribution, our next step is to relax the steady-state assumption in the interconnection field, which is work in progress.

V. *ELECTRIC FIELD IN THE CLOSED-FIELD-LINE REGION*

To extend the polar cap potential into the low-latitude ionosphere, we start from the continuity equation of electric current in the ionosphere,

$$\nabla_\perp \cdot (\Sigma \cdot \nabla_\perp \Phi) = j_{\parallel} \sin\chi$$

Since all the quantities in the above equation, Σ, Φ, and $j_{\parallel}$, are unknown, we have to make assumptions to simplify the equation and make it solvable, as summarized below:

Field aligned currents are idealized as and concentrated on two nearly concentric bipolar rings, similar to the model of Siscoe and Crooker [1983]. $j_{\parallel}$ is zero in between, i.e., in the domain of our solution.

The poleward boundary shape and the potential on it are given by the open field model.

The equatorward boundary represents the inner edge of the ring current in steady-state shielding theory, which is mathematically equivalent to the addition of an effective Hall conductance, proportional to the ring-current flux-tube content, in parallel with the ionosphere [Vasyliunas, 1972]. In the limit of perfect ring-current shielding, the Region-2 ring is equipotential and can be assumed to be at zero potential [Siscoe and Crooker, 1983], corresponding to equal flux transport across the dawn and dusk meridians.

The position of the equatorward boundary can be empirically related to the IMF B_Z component [Siscoe, 1991; and references therein], or to the polar-cap potential drop [Siscoe, 1982; and reference therein]. For simplicity, we use a non-offset constant of latitude as the equatorward boundary and its location is an input.

The conductivity tensor including the Pedersen conductivity and Hall conductivity is uniform and anti-symmetric in the solution domain.

Because we focus on (relatively high) auroral latitudes, the variation in the z direction is ignored. This simplifies the spherical coordinates to simple Cartesian coordinates. The equation can be further simplified as a two-dimensional Laplace equation.

Because of the irregularities of the shape of the polar cap boundary and equatorward boundary, we use the method of finite elements. (A detailed description of the potential solver is given by Ding [1995].) The domain is discretized into a finite mesh [Figure 7a], where four-node bilinear finite elements are utilized.

A sample result of the potential solver is shown in Figure 7b. The contours are symmetric because of southward IMF. The potential interval is 4 kV. The potential at equatorward boundary is zero. Owing to data smoothing in contour plotting, the open-closed boundary is not exactly at the flow reversal, which is an artifact and should not be taken seriously. The potential solver is flexible and versatile enough to handle any shape of boundary, and any open magnetic field model. Figure 8 shows two cases for nonsouthward IMF to demonstrate the flexibility of the model.

Because the convection electric field is provided on both sides of the open-closed boundary, we are able to calculate the field aligned currents on those boundaries. These predicted field aligned currents in the ionosphere will facilitate us in future modeling of the field produced by the field aligned current, which is the last major magnetic source not included in the Toffoletto-Hill model. This remains for future work.

SUMMARY

Many upgrades have been made to improve the existing Toffoletto-Hill open magnetosphere model.

- ♦ A new magnetopause current module has the ability to model a more general interconnection field.
- ♦ The inclusion of a realistic shielded ring current field compensates the southward tail field near the subsolar point, and also improves the accuracy of the representation of inner magnetosphere.
- ♦ Modification of the additional tail field eliminates the artificial negative B_Z problem near the dawn and dusk flanks.
- ♦ The numerical electric potential solver completes the electric field representation.

We are now developing a user-friendly version of the model code. The code will be available on the internet as soon as it is finished. Watch the WWW homepage of Rice magnetic field models (http://rigel.rice.edu/~ding/rfm.html) for updates.

The new improved model, once on-line, can be ready to be utilized for various investigations requiring mutually consistent global electric and magnetic fields, such as particle tracing, magnetic mapping, and data analysis.

ACKNOWLEDGMENT

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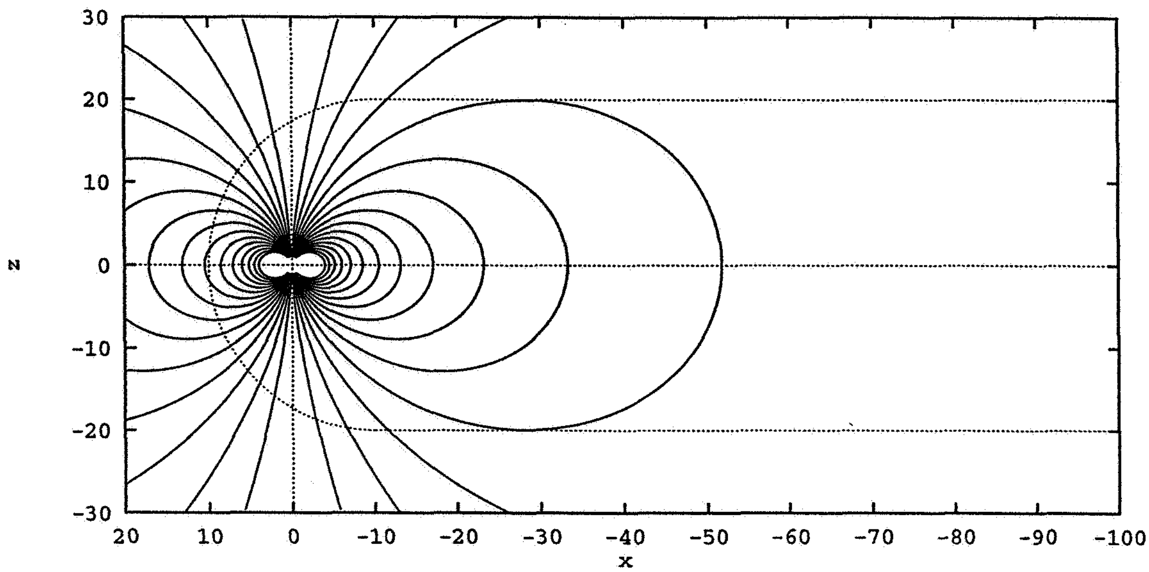

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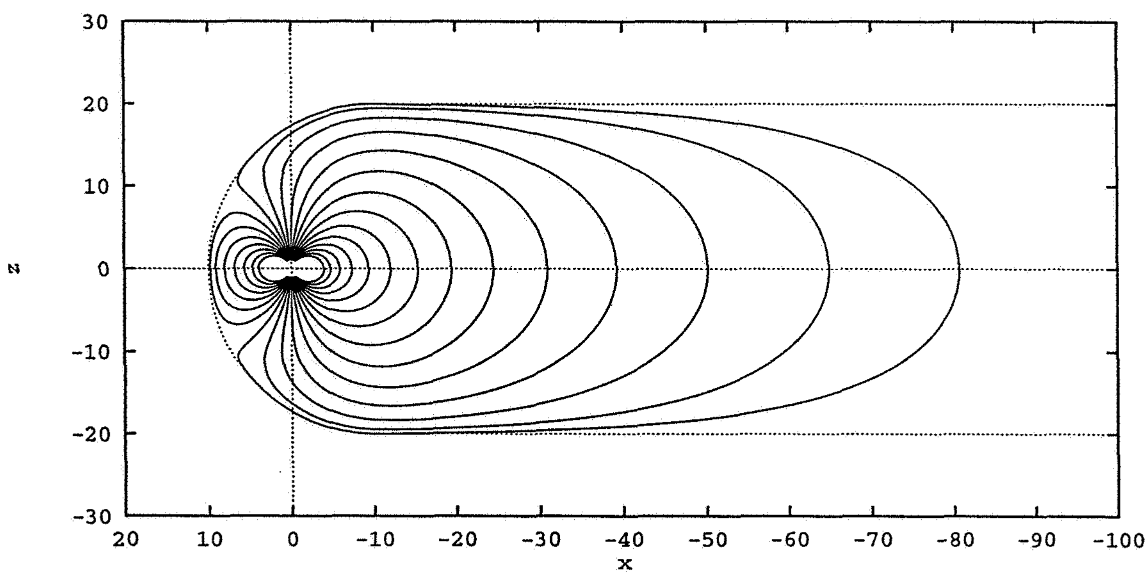


(b)

Figure 1. The dipole field plotted in the noon-midnight meridian plane. (a). The unshielded configuration. (b). The shielded configuration.

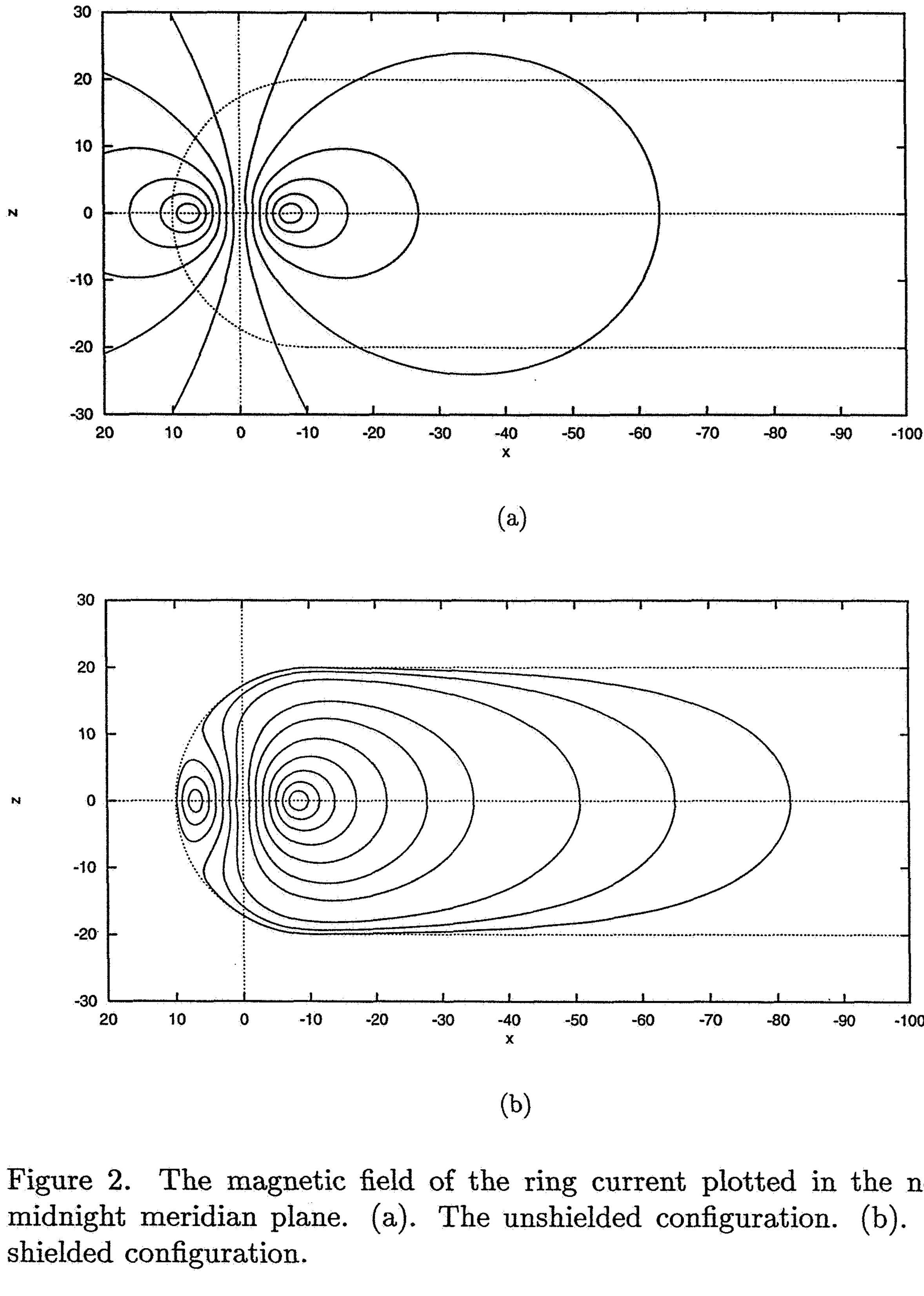
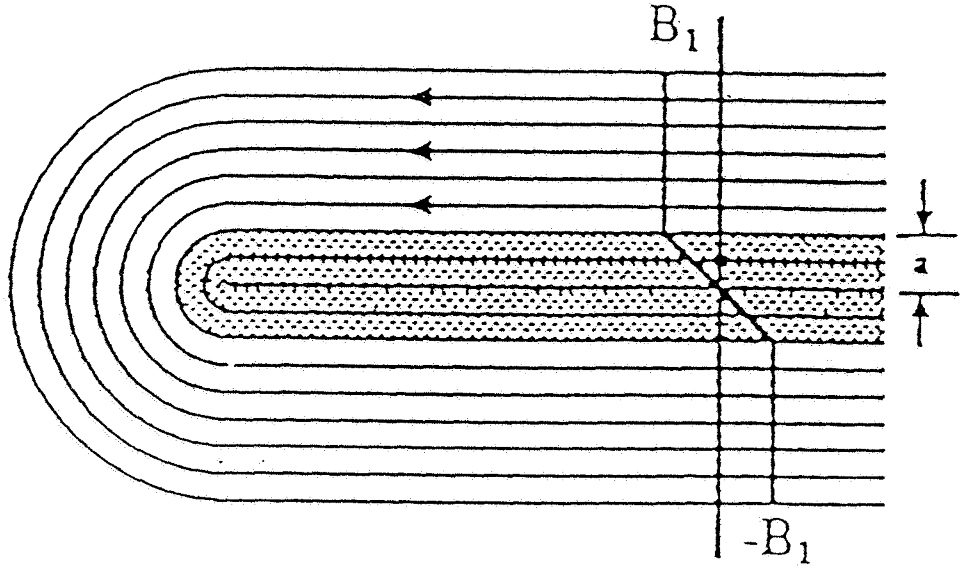


Figure 2. The magnetic field of the ring current plotted in the noon-midnight meridian plane. (a). The unshielded configuration. (b). The shielded configuration.



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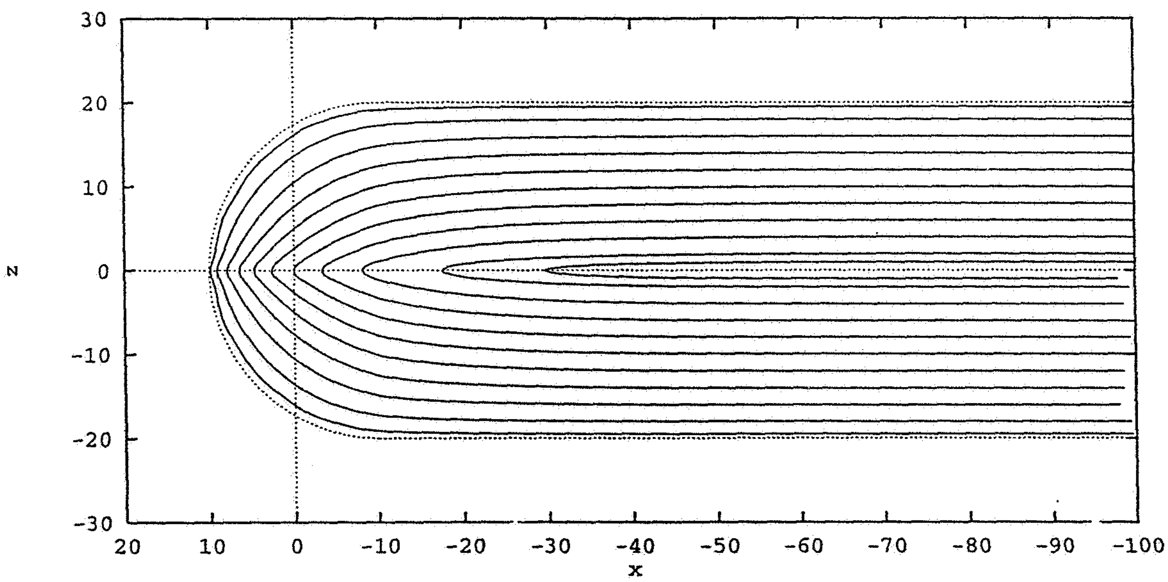
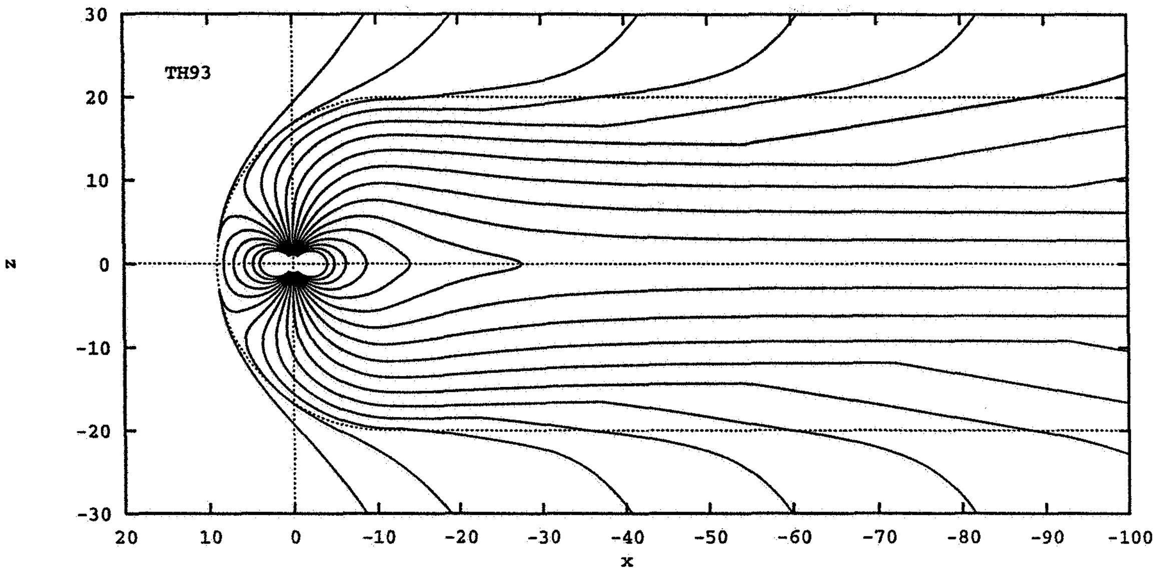


(b)

Figure 3. The configuration of the additional tail field in the noon-midnight meridian plane, in (a) the Toffoletto and Hill [1989, 1993] model, (b) the new version.



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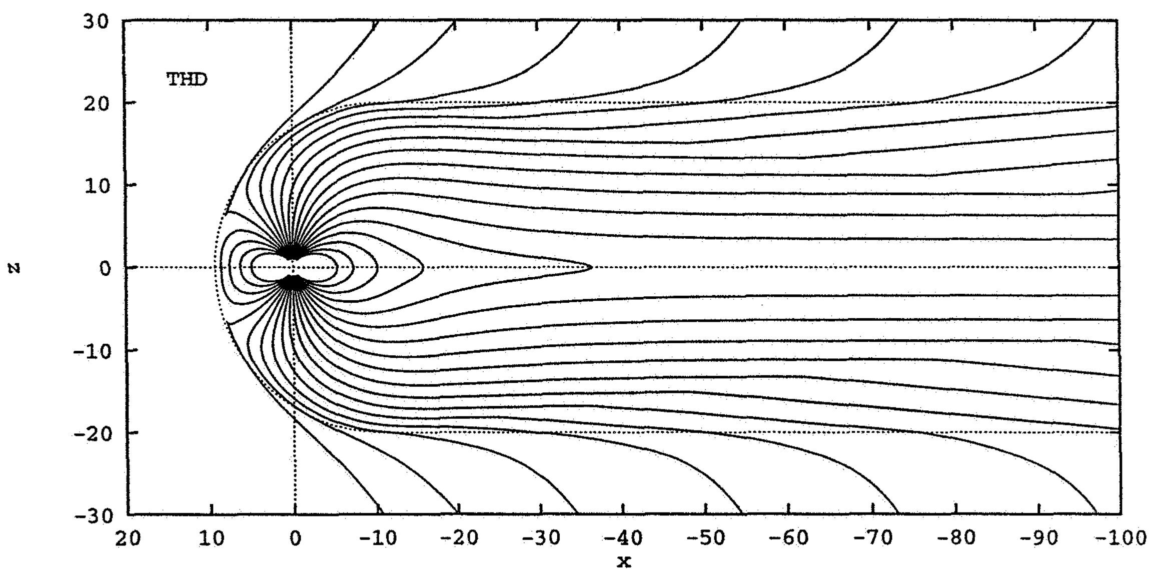
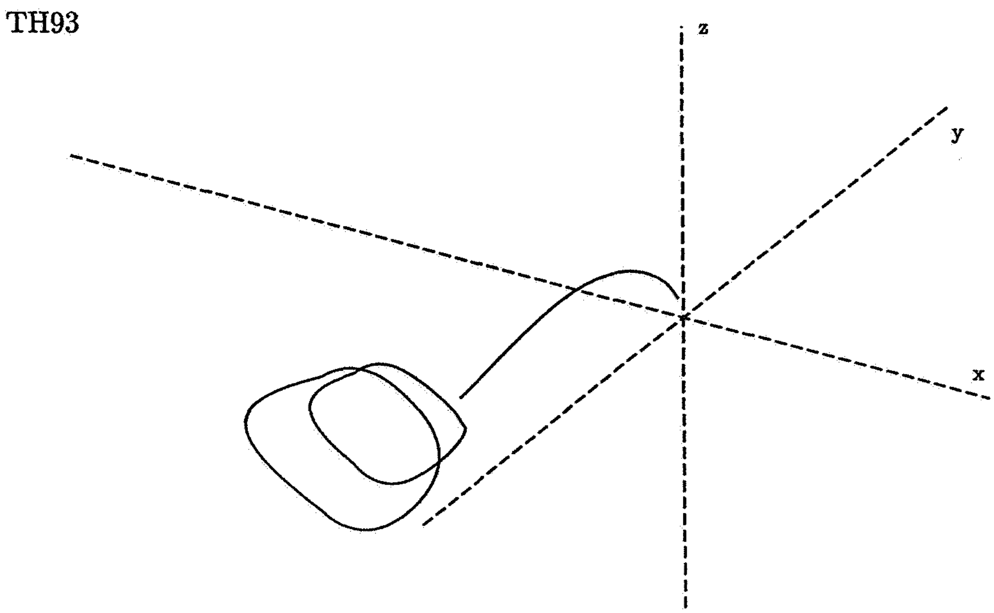


(b)

Figure 4. The total magnetic field plotted in the noon-midnight meridian plane (a) of the Toffoletto and Hill [1993] model, (b) of the new version.



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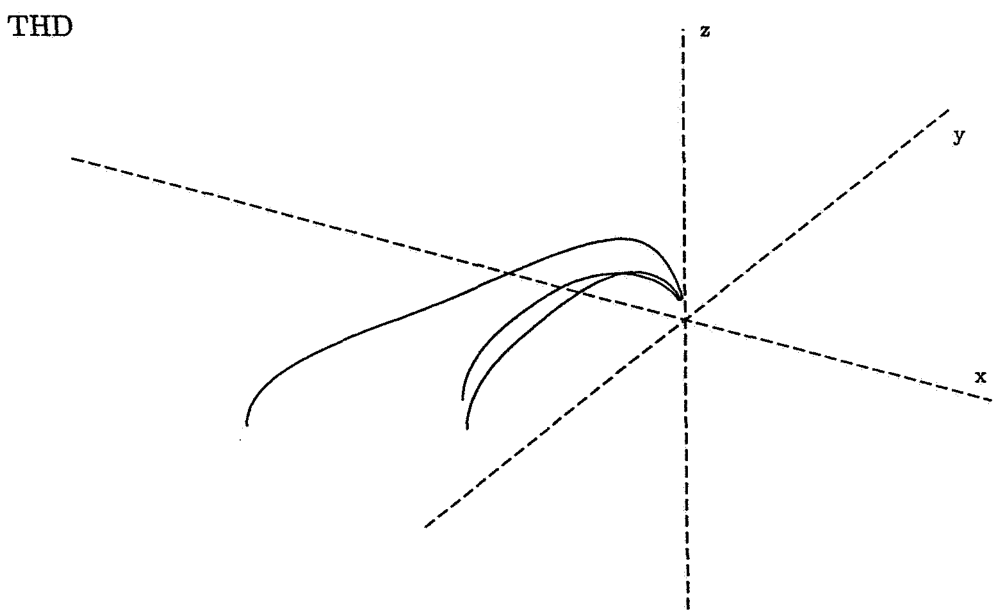
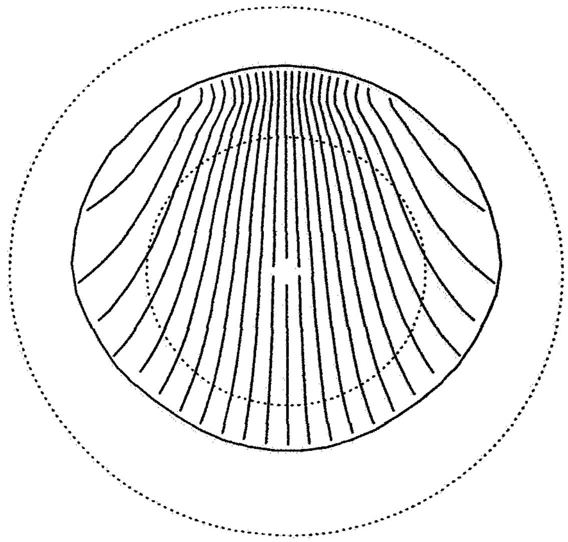


(b)

Figure 5. Magnetic field lines started from (-6,-10,0), (-4,-12,0), and (-15,-16,0) in (a) the Toffoletto and Hill 1993 model, (b) the new improved model.



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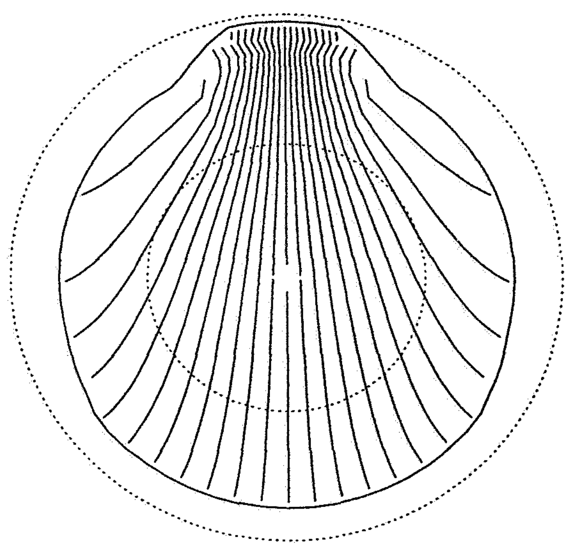


(b)

Figure 6. Polar cap potential mapped from the solar wind when the IMF is southward (-6nT) (a) the Toffoletto and Hill [1993] model, (b) the new version.

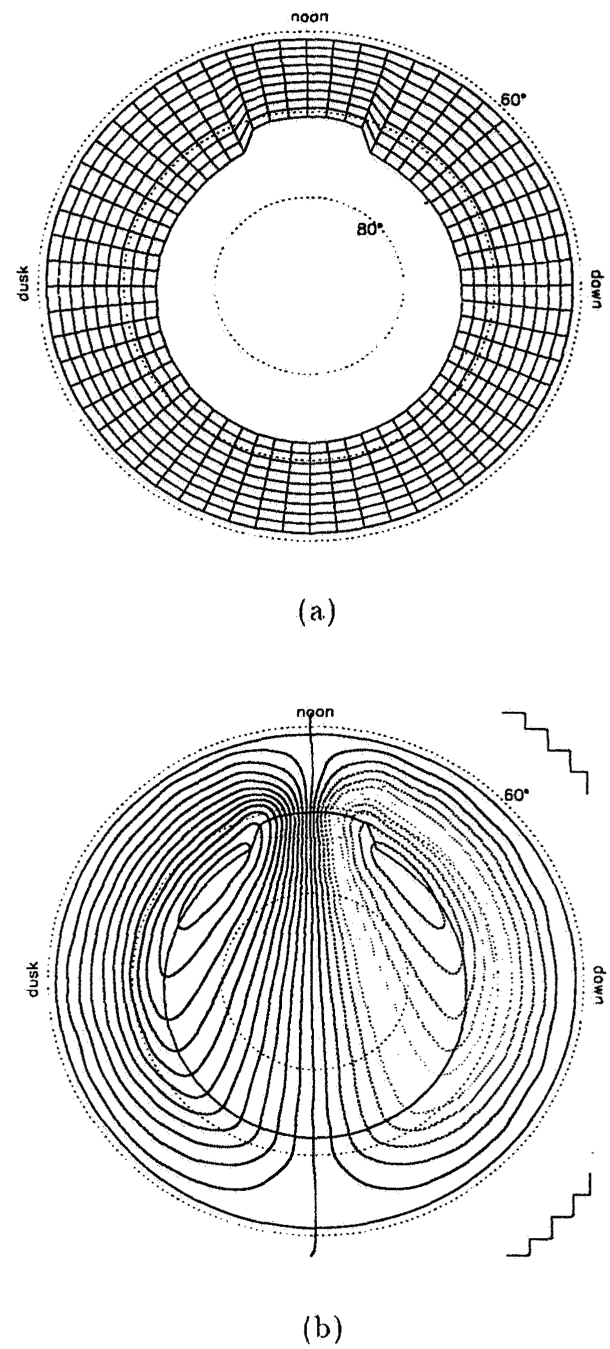
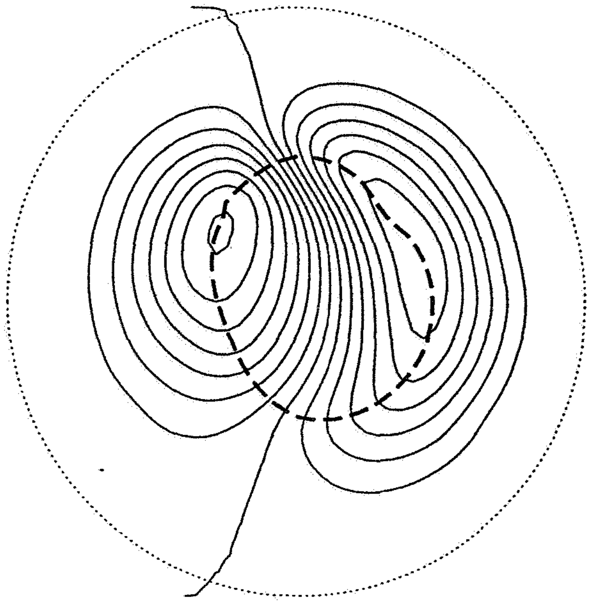
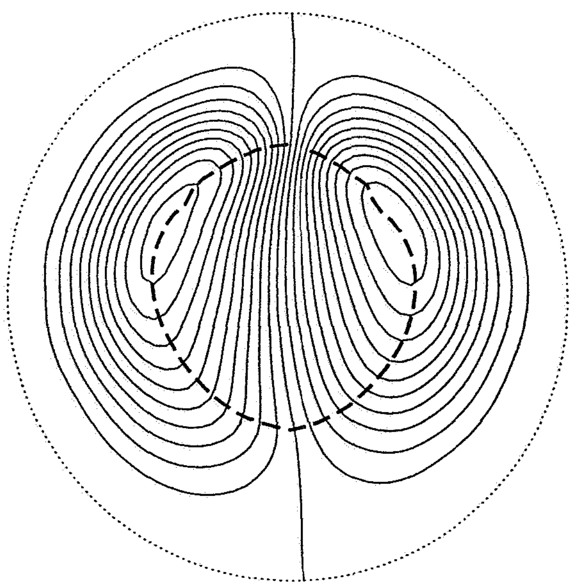


Figure 7. (a). The numerical grid used to solve the potential in the closed-field-line region. (b). The ionospheric potential including both open and closed field line regions.



(a)



(b)

Figure 8. Ionospheric electric potential patterns for IMF x,y,z components (a) (0, 4 nT, 4 nT), (b) (0, -6 nT, -1 nT).

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MODELING AND MAPPING OF ELECTRIC POTENTIAL ON CLOSED FIELD LINES

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ABSTRACT

A model of the electric potential on closed field lines is developed by extending the polar-cap potential into the low-latitude ionosphere using the finite element method. This provides the plasma return flow and completes the convection cells. By mapping it into the magnetosphere, the reasonability of the magnetic normal component distribution on the magnetopause can be examined.

I. MOTIVATION

The Toffoletto-Hill 1989, 1993 model [1, 2] is a theoretical construct of the open magnetosphere. It begins with a closed magnetosphere model and perturbs it with an interconnection field, based on Neumann-type boundary conditions on the magnetopause. The solar-wind motional electric field ($\mathbf{E}=-\mathbf{v}\times\mathbf{B}$) is then mapped along open field lines to drive the convection of plasma in the high latitude ionosphere and magnetosphere.

While faithfully modeling the electric potential on open field lines, however, the mapping model can not provide the electric potential on closed field lines. This is of little consequence if only theoretical interest is involved; however, it limits the application of the model in practice. For example, one of the basic model applications is to use the mutually consistent electromagnetic field to trace particle motion in the magnetosphere. However, the tracing has to stop on or close to the closed field line region because the electric field, the gradient of the electric potential, is not provided there.

To overcome this shortcoming, a rough estimate has been provided for the potential on closed field lines in the distributed version of the Toffoletto-Hill 1993 model code [3], based on the computed potential distribution at the tail X-line and the assumption of straight sunward flow on closed field lines. The result is less accurate for nonsouthward IMF since the neutral sheet twists around with increasing distance downstream from Earth in response to IMF torque, and the potential is determined by the distance from the footprint on the neutral sheet to the magnetopause intersection of the neutral sheet. Also, the ring current shielding effect is not included in the near-Earth region. The work described here presents another approach to this problem, which is more accurate and more versatile.

We emphasize that the main purpose here is to complete the open model and to meet the practical needs of the research community. Most of the physics discussed here is not new and has been extensively studied elsewhere, for example, by the Rice Convection Model [4].

II. ASSUMPTIONS

To extend the polar cap potential into the low-latitude ionosphere, we start from the continuity equation of electric current in the ionosphere,

$$\nabla_{\perp} \cdot \left(\Sigma \cdot \nabla_{\perp}\Phi\right) = j_{\parallel} \sin\chi$$

Since all the quantities in the above equation, Σ, Φ, and $j_{\parallel}$, are unknown, we have to make assumptions to simplify the equation and make it solvable. We summarize our assumptions as follows. Field aligned currents are idealized as two nearly concentric bipolar rings, similar to [5]. The Region-1 driving current is concentrated on the poleward boundary, i.e., the open-closed boundary that is already given in the open model; the Region-2 shielding current is concentrated on the equatorward boundary, a few degree equatorward of the polar cap boundary. (We will discuss the location of the Region-2 ring below). The field aligned current density $j_{\parallel}$ is zero in the region between these boundaries, i.e., our solution domain. The potential on the poleward boundary is given by the open model as a Dirichlet-type boundary condition. The equatorward boundary, i.e. the Region-2 ring, represents the inner edge of the ring current in steady-state shielding theory, which is mathematically equivalent to the addition of an effective Hall conductance, proportional to the ring-current flux-tube content, in parallel with the ionosphere [6, 7]. In the limit of perfect ring-current shielding, the Region-2 ring is equipotential and can be assumed to be at zero potential [5]. This is equivalent to assuming that equal amounts of flux are transported past the Earth on the dawn and dusk sides. In the solution domain, the conductivity tensor including the Pedersen conductivity and Hall conductivity is uniform and anti-symmetric. Because we focus on (relative high) auroral latitudes, the variation in the z direction is ignored. This simplifies the spherical coordinates to simple Cartesian coordinates. The equation then simplifies to a two-dimensional Laplace equation.

$$\frac{\partial^2\Phi}{\partial x^2} + \frac{\partial^2\Phi}{\partial y^2} = 0$$

The position of the equatorward boundary can be empirically related to the IMF B_Z component [8], or to the polar-cap potential drop [9]. For simplicity, we use a non-offset constant latitude ring as the equatorward boundary, and its radius is an input parameter.

III. NUMERICAL PROCEDURE

Even with the above assumptions, it is impossible to find an analytical solution because of the irregularities of the shape of the polar cap boundary. Hence we use the method of finite elements to handle this complicated geometry. (The detailed description of the potential solver is reported in [10].) The domain is discretized into a finite mesh [Figure 1a], where four-node bilinear finite elements are utilized.

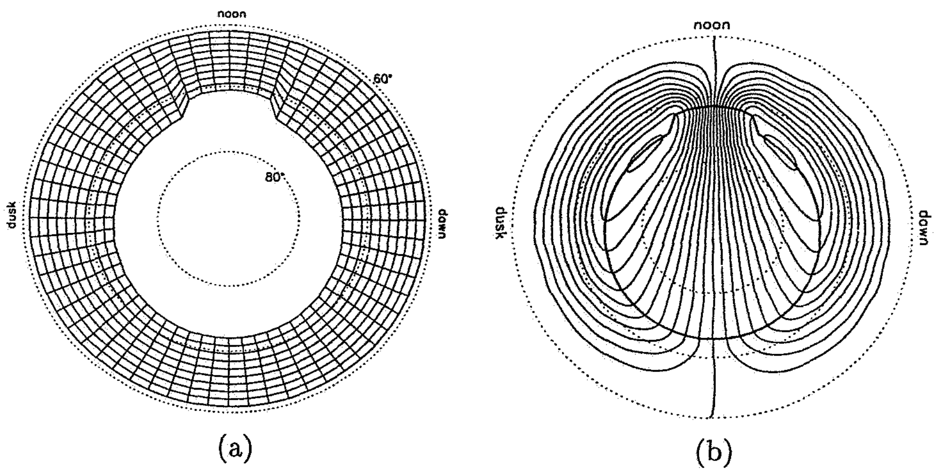
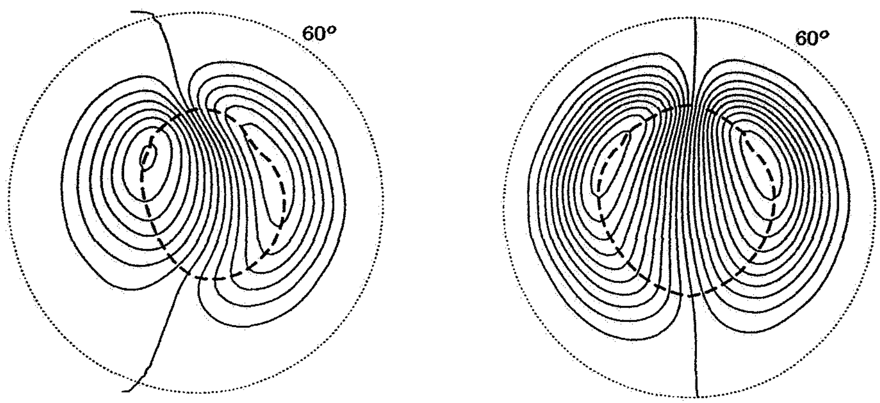


Figure 1. (a) Grid used to solve the electric potential in the low-latitude ionosphere. (b). The ionospheric potential pattern including both open and closed field line regions.

Figure 1b shows the result of the potential solver for the mesh in Figure 1a. The contours are symmetric because of southward IMF. The potential interval is 4 kV. The potential at the equatorward boundary is zero. Owing to data smoothing in contour plotting, the open-closed boundary is not exactly at the flow reversal; this is an artifact and should not be taken seriously.

The model is flexible and versatile with respect to the shape of the boundaries, and the nature of the open magnetic field model. Figure 2 shows two cases for nonsouthward IMF to demonstrate the flexibility of the model. The location of the equatorward boundary should be determined more precisely as a function of IMF conditions or the polar-cap potential drop. This can be done with guidance obtained directly from observations or from other studies such as RCM, or even from the mapping of the electric potential into the magnetosphere as discussed in the next section.



(a) (b)

Figure 2. Ionospheric potential patterns under nonsouthward IMFs, (a) (0, 4 nT, 4 nT), and (b) (0, -6 nT, -1 nT).

Because the convection electric fields are provided on both sides of the open-closed boundary, we are able to calculate the Region-1 driving currents implicitly given in the ionosphere. The Region-2 shielding current can also be determined by the adjacent Region-1 current. These predicted field aligned currents in the ionosphere will facilitate us in future modeling of the field produced by the field aligned current, which is the last major magnetic source not included in the Toffoletto-Hill model. This has been left for future work.

Computational time is relatively fast. For a typical grid of 60×10, the model takes about one minute on a HP workstation.

IV. MAGNETOSPHERIC MAPPING

As an application of this complete electric potential model, and to check if the calculated electric potential is reasonable, we map the closed-field-line potential into the magnetospheric equatorial plane, assuming there are no parallel electric fields. We only show the purely southward IMF case for simplicity.

The equipotentials on the magnetospheric equatorial plane are shown in Figure 3, with the effect of corotation excluded. The electric field is primarily in the dawn to dusk direction, and the associated magnetospheric convection is mainly sunward **E**×**B** drift in the distant tail. The shielding effect of the ring current is clearly visible in the inner magnetosphere. The position of zero potential is at x=4.99 R_E at local noon and x=-5.31 R_E at midnight. It is commonly accepted that the plasma sheet convection is uniformly distributed in the *y* direction or even weaker at the center of the tail than at the flanks.

This potential pattern is a reflection of how the potential, and the magnetic normal component, is distributed on the magnetopause, because both the poleward potential boundary condition and the mapping are determined by the distribution of the normal component. Therefore, the results shown in Figure 3 can be helpful in assessing the validity of the assumed normal component distribution. We have studied other types of normal component distribution. We found that a narrowly peaked distribution of normal component will give a narrowly peaked distribution of the equatorial plasma convection. The results suggest that a $\cos^3\psi$ dependence in equation 4 of [2] as used in Figure 3 is more acceptable than a sharply peaked $\cos^7\psi$ dependence.

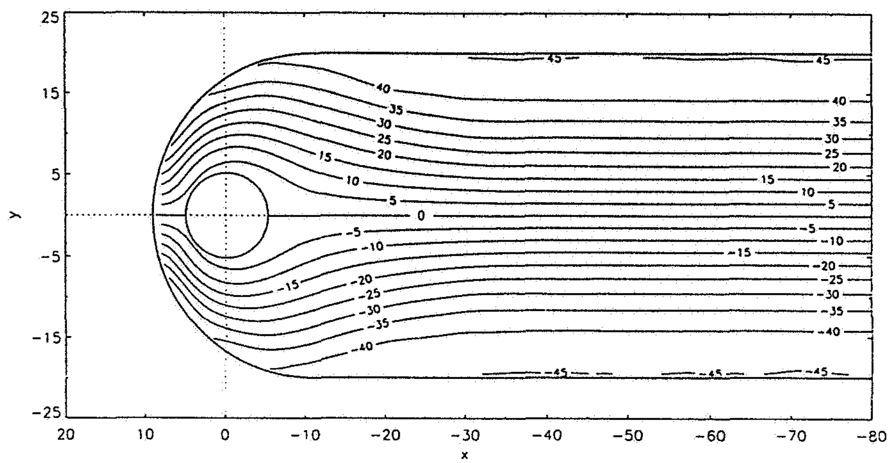


Figure 3. Equatorial electrical potential mapped from the ionosphere of Fig. 1b. The corotation field is not included in this plot.

It is worth pointing out that field aligned currents, which are not yet included in the Toffoletto-Hill model, would increase the flaring of plasma sheet field lines, and thus enhance the earthward convection at the flanks compared to the center of the tail.

V. SUMMARY

We have demonstrated a numerical model that provides the electric potential on closed field lines, thus enhancing the utility of the Toffoletto-Hill open model, or any other electric-field-mapping model, in the following ways: The open model is complete now in the sense that the electric field is fully provided. That means the model can be utilized for particle tracing and many other investigations of multiscale processes connected with global electric and magnetic fields. Adding the low-latitude return flow and completing the convection cells improves the ability to compare with observations. The calculated potential can predict field aligned currents in the ionosphere, which will facilitate us in future modeling of the field aligned current, and improve the self-consistency of the model.

This model of closed-field-line potentials is very simple as it now stands. We will continue to reduce the simplifications and improve the model, for example, by using a more realistic model of ionospheric conductivity [11]; including the effect of Region-1 and -2 field aligned currents; and adjusting the magnetopause normal component distributions.

ACKNOWLEDGMENT

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IMPROVEMENT OF THE TOFFOLETTO-HILL OPEN MAGNETOSPHERE MODEL

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ABSTRACT

The Toffoletto-Hill 1993 open magnetosphere model is improved by the modification of the dayside closure of its additional tail field to eliminate the negative B_Z region at the dawn and dusk flanks, and by the addition of a fully-shielded ring current field model to better represent the inner magnetosphere. The new improved model can be used for various investigations of multiscale processes connected with global electromagnetic fields.

I. MOTIVATION

The Toffoletto-Hill 1989, 1993 model [1,2] (TH89, TH93 for short) is a theoretical construct of the open magnetosphere. It begins with a closed magnetosphere model [3] with a composite magnetopause and perturbs it with two magnetic modules, an interconnection field, which models the coupling between the IMF and the geomagnetic field, and an additional tail field, which approximates the effect of the tail current.

In TH89, the interconnection field is the gradient of a scalar potential that solves Laplace's equation inside the magnetopause and satisfies a Neumann type boundary condition on the magnetopause. The additional tail field lines are straight lines in the $\pm x$ direction in the cylindrical region and semicircles in the hemispheric region, which removes dayside magnetic flux and transports it to the tail lobe, and consequently makes the polar-cap size, shape and position realistic. TH93 modified the interconnection field in order to remove the mapping singularity for nonsouthward IMF. The interconnection field, theoretically specified now, has its field lines in the tail being forced to cross the equator tailward of a prescribed concave tail X line. The additional tail field now has to be strengthened to counteract the tailward interconnection field and maintain a tail like configuration. The total field has an expansion fan inside the high-latitude tail magnetopause, and the mapping singularity is successfully removed.

The model, however, implicitly includes a problem for a case with a large southward IMF. When the IMF southward component, and the interconnection field due to IMF penetration, is large, a much stronger tail field is needed to turn the interconnection field towards Earth. The dayside closure of such a strong tail field across the equatorial plane can reverse the northward B_Z of the dipole field and produce an extraneous southward field region near the equatorial dawn and dusk flanks [Figure 1].

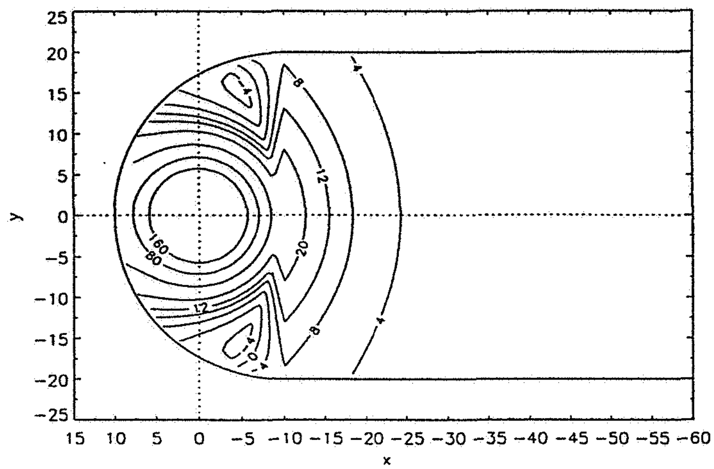


Figure 1. Equatorial B_Z in the Toffoletto-Hill 1993 model when the IMF is (0,0,-6nT). Note the negative B_Z region near the dawn and dusk flanks.

Besides the above negative B_Z problem, the TH model, like the Voigt model [3] on which it is based, lacks a geomagnetic ring current. Inclusion of a ring current would help to reduce the negative B_Z problem and improve the magnetic mapping in the inner magnetosphere.

II. NEW TAIL FIELD MODEL

The cause of the negative B_Z problem is the dayside closure of the additional tail field. It is necessary to modify the semicircular closure of the additional tail field to fix the problem. First we let the nightside tail field lines go straight and pass through the dayside magnetopause, which contributes no southward B_Z on the equatorial plane. However, this move severely violates the boundary condition for the interconnection field on the dayside magnetopause. Therefore we apply a shielding algorithm [4] and shield the field inside the magnetopause [Figure 2].

Instead of being artificially confined within the hemisphere, the equatorial B_Z of the new additional tail field [Figure 3] is distributed three dimensionally within the magnetopause. The maximum southward B_Z is at the region near the subsolar point. To ensure the total magnetic field at the subsolar point mantains a reasonable magnitude, a ring current field which gives positive B_Z there is needed.

This modification of the additional tail current also eliminates the spurious current due to the curvature of the semicircular field lines within the dayside magnetosphere. The spurious current now is reduced in amount and confined near the equatorial plane. The tail current extended into the dayside region will be reduced by the ring current, while in the nightside region it will be strengthened by the ring current.

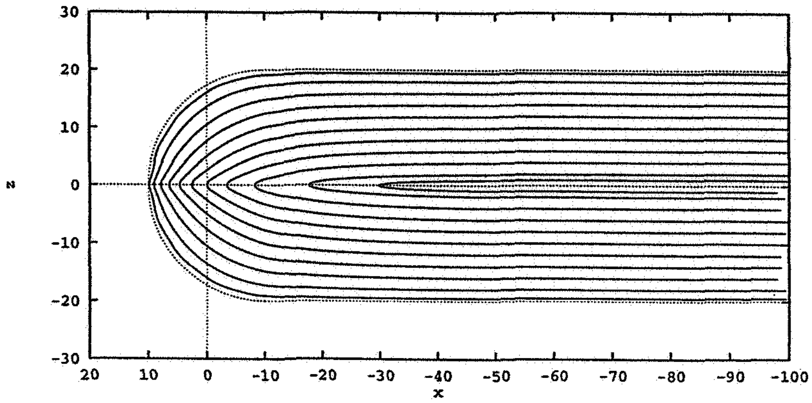


Figure 2. The new additional tail field.

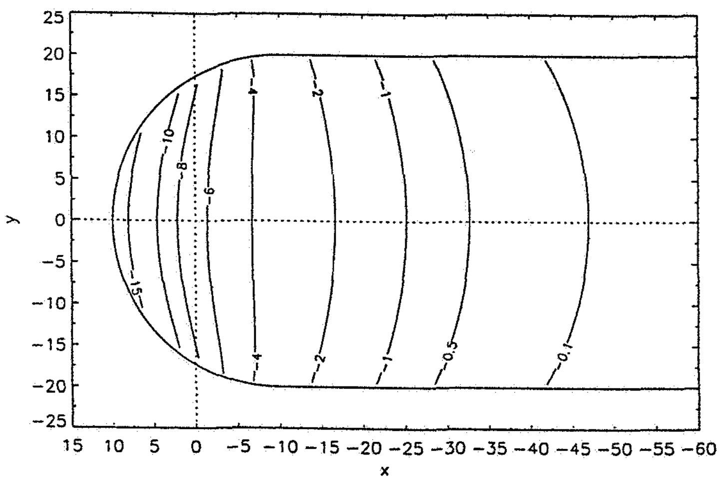


Figure 3. Equatorial B_Z of the new additional tail field.

III. RING CURRENT FIELD

Ring current models come in many different forms and have been developed for a variety of different purposes. We adopt the ring current model developed by Hilmer and Voigt [5]. Once again we apply the shielding algorithm [4] to the ring current model before adding it into the open model so as not to compromise the boundary condition for the interconnection field. Figure 4 shows the field lines of the ring current model.

We will adjust the ring current strength to keep the field strength at the subsolar point reasonable and to hold the southward B_Z effect at the dawn and dusk flanks produced by the additional tail field to a relative minimum. It is interesting that our model requires the ring current field to be strengthened when the IMF B_Z component becomes bigger, consistent with general observations.

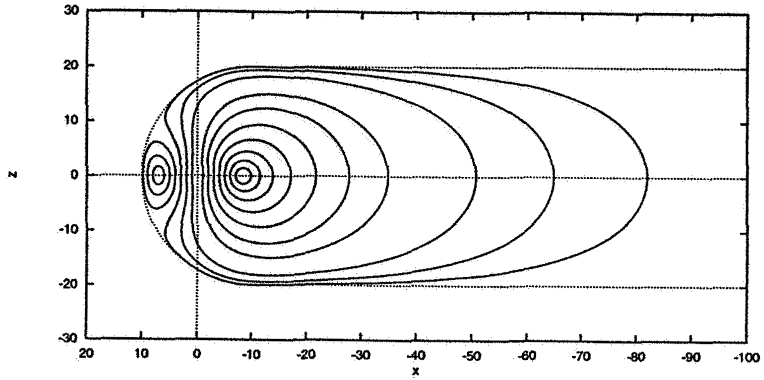


Figure 4. The field configuration of a fully-shielded ring current field.

IV. NEW CONFIGURATION

The new equatorial B_Z distribution of all the magnetic field sources [Figure 5] is now smooth and has no negative B_Z region like those in Figure 1. The unphysical kink at the junction of the hemisphere and cylinder is also removed. Other reasonable combinations of input parameters give similar results.

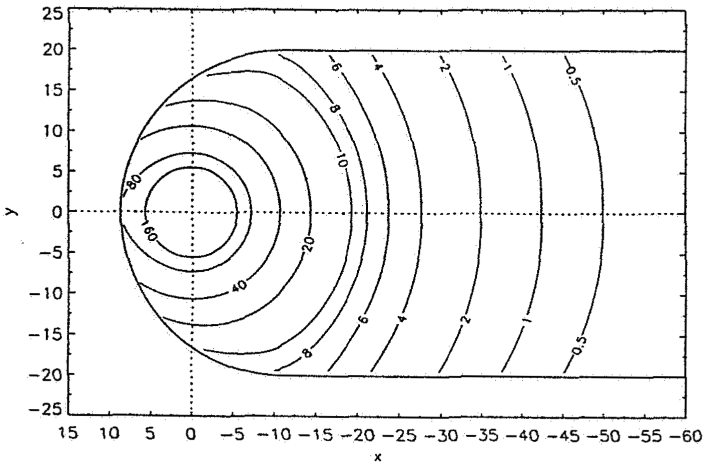
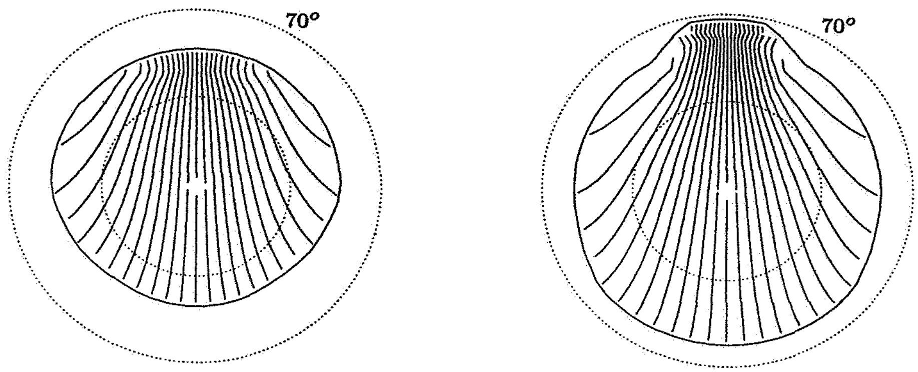


Figure 5. Equatorial B_Z distribution of the new improved model under the same conditions as Figure 1.

We have compared the field configurations between the TH93 model and the improved version. Not too much difference is found in the noon midnight plane except that the ring current pushes the inner field lines outward and makes the magnetosphere more open. The differences at the dawn and dusk flanks are larger than in the noon-midnight plane because some field lines in the original version form closed loops at the flanks. Comparison between Fig. 4 and Fig. 1 can provide an aid to the imagination.

We also calculate the polar potential for this case [Figure 6]. The bigger open-field-line region in the new model is the results of the modification of the additional tail field and the inclusion of the ring current.



(a) (b)

Figure 6. Polar cap potential pattern in (a) the Toffoletto-Hill 1993 model and (b) the new improved model, both under the same IMF conditions.

V. SUMMARY

Modification of the additional tail field eliminates the negative B_Z problem near the dawn and dusk flanks. The inclusion of a realistic fully-shielded ring current field compensates the southward tail field near the subsolar point and also improves the accuracy of the representation of the inner magnetosphere. This new improved portable model can be utilized for particle tracing, magnetic mapping, and data analysis. The model code is available over the internet; please see the instructions in the WWW page "http://rigel.rice.edu/~ding/rfm.html".

ACKNOWLEDGMENTS

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Towards a New-Generation Model of the Open Magnetosphere

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To provide the research community a realistic, portable and complete electromagnetic field model of the open magnetosphere, we have made several improvements to the Toffoletto-Hill (1993) model, these improvements include: (a) modificiation of the dayside closure of the additional tail field in the model to eliminate shortcomings in the previous U-shaped additional tail field; (b) a realistic, fully-shielded ring current field to improve the representation of the inner magnetosphere and compensate the artifact caused by the interconnection field and additional tail field for a large IMF B_z condition; (c) a potential solver to reliably provide the electric potential on closed field lines in the ionosphere thus completing the high-latiitude convection cells.

The source code of the new improved portable model will soon be available on the Internet. This model can be utilized for various investigations connected with global electric and magnetic fields, and will provide a background electric and magnetic field for particle tracing.

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